Bit Error Rate Measurement of Free Space Optical Communication Links under Laboratory-Controlled Fog Conditions

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***Abstract*—This paper outlines the experimental investigation of the fog effect on the bit error rate (BER) performance of the free space optical (FSO) communication link under a controlled laboratory environment. The link transmittance and the received signal *Q*-factor are measured against different levels of fog densities. The link visibility derived from fog attenuation measurement is used to characterize the fog within the chamber. Moreover, the effect of using different average transmitted optical communication power (P_{opt}) on the transmittance and received *Q*-factor of the link is also studied for light and dense fog densities.**

***Index Terms*— Fog, Free space optics, Transmittance, Visibility**

I. INTRODUCTION

In recent years, the demand for a back up and complementary link to the radio frequency technology particularly for the "last mile" in access network based on the FSO system has increased considerably [1, 2]. This is due to a number of key advantages including a large un-regulated and license free transmission bandwidth spectrum, a large data transmission, consumption of low power, security as well as immunity to the electromagnetic interference [3, 4]. Despite these advantages, the performance of FSO links is largely dependent on the weather condition [5]. Fog compared to other atmospheric constituents is the dominant source for the optical power attenuation, thus potentially reducing the FSO link availability. This attenuation varies from 0.2 dB/km for a clear weather to as high as 130 dB/km and 480 dB/km for the moderate continental fog and the dense maritime fog respectively [5-7]. In practice, it is very challenging to measure the effect of the atmosphere constituents like fog under diverse conditions and locations. This is mainly due to the long waiting time to observe and experience reoccurrence of different atmospheric events. In addition measurement equipment and system required are complex and costly. To be able to carry out complete system measurement under all weather conditions, we have developed a dedicated laboratory atmospheric chamber to investigate the effects of fog, smoke, temperature induced turbulence and wind on the propagating optical beam. The chamber enable us to carry out the outdoor FSO system characterisation and performance measurement under a controlled environment without the need for longer waiting times as would be in the case of out-door FSO links.

The effect of fog on the BER performance of an FSO link is reported in [8] which correlates the atmospheric transmission with the BER. However, this work does not study in details the atmospheric transmission characteristics of the fog channel by increasing different average optical communication power P_{opt} to improve the BER performance of FSO. In this paper, we introduce an alternative approach to evaluate the BER performance of the FSO link under fog environment using the real time domain received signal eye diagrams. Here, we measure the transmittance T as well as the signal-to-noise ratio (SNR) (i.e. the Q-factor) for a given value of P_{opt} for light-to-dense fog densities. We show that for the proposed FSO system operating at Q-factor of 4.7 (BER = 10^{-6}), the required Q-factor is achieved at T of 48 % under the thick fog condition by increasing P_{opt} to 1.07 dBm, whereas the values of T are 55 % and ~70 % for the transmit power of 0.56 dBm and -0.7 dBm, respectively. The paper is organized as follows: The BER performance of the FSO link in the fog channel is outlined in Section 2, whereas experimental investigating of the fog effect is introduced and explained in Section 3. In Section 4 results and discussion are presented. The conclusions and future works are discussed in the Section 5.

II. BIT ERROR PERFORMANCE OF FSO IN FOG CHANNEL

A. *Fog and Visibility*

The constituent of atmosphere consist of many types from gases to aerosols. Amongst the particles that attenuate the optical beam due to the Mie scattering is the fog, which consists of very fine spherical particles of water suspended in the air with variable particle size (1-25 μm in diameter) [9]. Fog particles reduce the visibility near the ground and the meteorological definition of fog is when the visibility drops to near 1 km. Different types of fog are categorized based on a number of factors including the location, the particle size distribution and the average particle diameter. As the particle concentration and the size distribution are varied in the spatial domain, it is challenging to predict the fog induced attenuation in the channel [10].

Link visibility (i.e. the meteorological visual range) is used to measure the attenuation due to the fog. Koschmieder has defined the visibility as the distance to an object at which the visual contrast of an object drops to 5 % of the original visual contrast (100 %) along the propagation path [11]. This 5 % drop value is known as the visual threshold T_{th} of the atmospheric propagation path. The meteorological visibility V (km) can be therefore expressed in terms of the atmospheric attenuation coefficient at a given wavelength and T_{th} as:

However, the scattering co-efficient due to the fog is the parameter that is dependent on the wavelength of the propagating optical beam and the visibility. In [12] the Kim model was developed to take into account the wavelength effect, which is given as:

Here, is the maximum spectrum of the solar band, q is the coefficient related to the particle size distribution in the atmosphere defined as:

(3)

Note that the attenuation is independent from wavelength for low visibility (i.e. V < 500m) in dense fog conditions.

B. Bit Error Rate Evaluation

Assuming $I(f)$ and $I(0)$ are the intensity of the received optical signals with and without fog, respectively the transmittance T is given by the Beer Lambert law [13] as:

(4)

where z is the propagation length. However, we are interested in correlating the Q-factor and resulting BER for a range of transmittance of the received signal and for different fog conditions. The Q-factor, which represents the SNR at the receiver with no fog, is given as:

(5)

where T_o is the maximum transmittance and is equal to the unity. I_1 and I_0 are the average detected signal current for bit ‘1’ and ‘0’ where as σ_0 and σ_1 are the standard deviation of the noise values for bit ‘1’ and ‘0’.

However, with fog and assuming the ambient noise level does not change with fog density, the Q-factor can be approximated as:

(6)

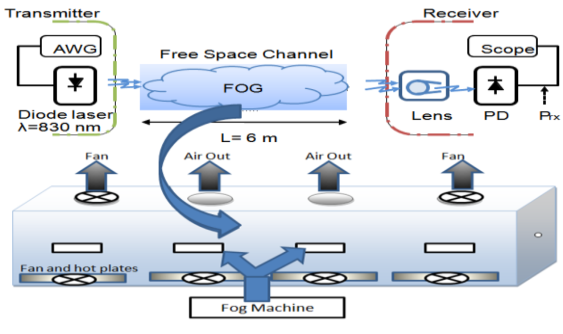
where T_{fog} is the transmittance measured in the presence of fog. For the non-return to zero on-off-keying (OOK-NRZ) data format with the intensity modulation and direct detection scheme, the BER expression for OOK-NRZ is given by:

(7)

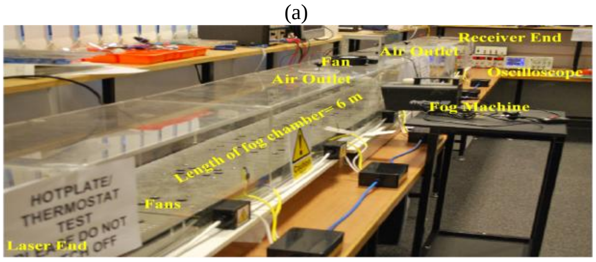
III. Experiment Description

The FSO link setup diagram used in this evaluation is shown in Figure 1 (a). A pseudorandom data sequence of 2^{13}– 1 bit length modulation using the OOK-NRZ signal format is applied to the laser source at a data rate of 25 Mbps. The intensity modulated optical beam propagates through the atmospheric chamber (600×30×30 cm^3 dimension) and is detected at the receiver composed of an optical concentration lens and a PIN photodetector integrated with a wide-bandwidth transimpedance amplifier.

The chamber has seven compartments each with a vent to allow air circulation using a fan. The fog is introduced to the chamber using a fog generator at a rate of 0.94 m^3/sec. The amount of fog injected into the chamber is controlled by a number of fans and ventilation inlet/outlets. Thus, allowing us to manage the fog flux within the chamber homogeneously and control the visual contrast (transmittance) of the FSO link. Both the average received optical power and the Q-factor of the received signal are simultaneously measured for different fog conditions i.e. from low to high visibilities.



(a)



(b)

Figure 1. (a) Block diagram of experiment setup, (b) The fog chamber and FSO link setup in the laboratory

Table I
EXPERIMENT PARAMETERS

Parameter		Value
Laser diode (transmitter)	Peak wavelength	830 nm
	Transmit optical power	10 mW
	Maximum peak to peak voltage	500 mV
	Beam divergence	<10 mrad
	Modulation bandwidth (max)	50 MHz
Photodetector (receiver)	maximum sensitivity (λ)	900 nm
	Spectral range of sensitivity	750 - 1100 nm
	Active area	1 mm^2
	Half angle field of view	± 75 Deg
	Spectral sensitivity @ 850nm	0.59 A/W
	Rise and fall time	5 ns
	Max. reversed bias voltage	40 V
Concentration lens	Diameter	3.4 cm
	Focal length	20 cm
Receiver	Transamplifier (IC)	AD8015
	Bandwidth	240 MHz
	Receiver sensitivity	- 32 dBm (at 25Mbps & BER = 10^{-6})

IV. RESULTS AND DISCUSSIONS

The experiment is carried out by filling the chamber with controllable amount of fog to achieve a range of very low to high visibility. In the experiment fog is allowed to settle down homogenously in the volume of the chamber before measurement is taken. The most critical impact of the fog is the attenuation of the optical beam by the Mie scattering and absorption. Both phenomenons are due to interaction of the particles with the electromagnetic waves propagating through the channel. This interaction depends upon the characteristic size of obstacle or particle, refractive index and the wavelength of the optical beam. Due to the very small refractive index value of imaginary part the absorption (Rayleigh scattering) in the infrared waveband by fog and aerosols is negligible [13]. The major contribution to dispersion of the beam is the particle size, which are approximately close the optical beam wavelength. In general both fog and haze that are major contributors to the Mie scattering due to the optical wavelengths being in the order of 1 - 15 μm.

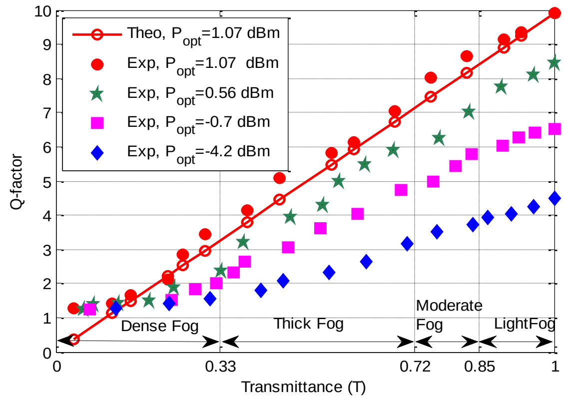
Due to the random nature and occurrence of the fog as well as its type, its effect on the FSO link performance can readily be measured and characterized by the visibility data. We evaluated the scattering co-efficient using (4) corresponding to the measured T at 830 nm. The visibility V is evaluated using (3) the wavelength dependent model known as the Kim model for < 500 m for a range of transmittance values, see Table II.

Table I
MEASURED T AND RELATED VISIBILITY VALUES

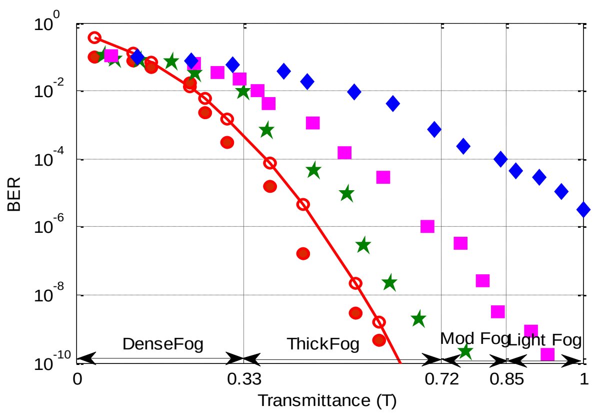
Fog	**Dense**	**Thick**	**Moderate**	**Light**
V (m)	< 70	70- 250	250-500	500-1000
T	< 0.33	0.33- 0.72	0.72- 0.85	0.85-0. 92

Figure 2 illustrates the dependence of Q-factor and the evaluated BER on the link transmittance for a range of P_{opt}. Also depicted are the predicted results for P_{opt} of 1.07 dBm showing a close agreement with the measured data. Note that in the region of T < 20 % (dense fog) the Q-factor values is almost the same for all values of P_{opt}. This is due to the background noise being the dominant source (see the eye diagrams in Figure 3). To achieve a BER of 10^{-6}, the Q- factor value must be ~ 4.7 for the OOK-NRZ data format. However, this Q-factor value cannot be achieved under the dense fog condition (i.e. T < 33 %) even for higher input power used P_{opt} = 1.07 dBm (see Figures 2(a) and (b)). With dense fog the link range drops to < 70 m with reduced link availability, thus making the FSO link less attractive for most access networks. In such cases one could increase the optical power provided it is kept below the eye safety level or switch to a lower data rate RF technology to maintain maximum availability of 99.999 %. For the thick fog condition (33 < T < 72 %) increasing P_{opt} from -0.7 dBm to 1.07 dBm increases the Q-factor from 2 to 7, respectively, thus corresponding to the BER improvement from 10^{-3} to $>10^{-9}$.

However, for the system with a P_{opt} of - 4.2 dBm it is not possible to achieve the required BER of 10^{-6} even where there is no fog, see Figure 2 (b). This is because P_{opt} is very low well outside the link power margin. The results also show that for moderate and light fog conditions, increasing P_{opt} from -4.2 dBm to -0.7 dBm achieves the required Q ~ 5 and a BER of 10^{-6}.



(a)



(b)

Figure 2. (a) Q-factor value and (b) BER of OOK-NRZ received signal versus the transmittance at different fog conditions and visibility zones (underlined) for a range of transmitted optical power

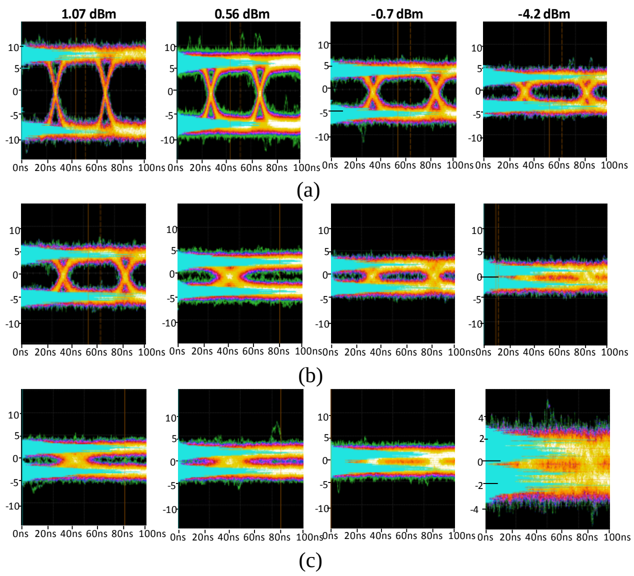


Figure 3. The received signal eye diagram for different P_{opt}, time scale is 20 ns/div, voltage scale is 5 mV/div: (a) for 100 % transmittance, (b) for 50 % transmittance, and (c) for 30 % transmittance

The received signal eye diagrams for T of 100 %, 50 % and 30 % are displayed in Figure 3. For P_{opt} = 1.07 dBm, the average opening of the eye decreases from the maximum value of 11.55 mV at T = 100 % to 4.54 mV and 0.042 mV for T = 50 % and 30 %, respectively, thus indicating the considerable effect of fog on the received signal quality. Also note that the histograms of top and bottom of the eye diagrams, corresponding to bits ‘1’ and ‘0’, respectively, are Gaussian in shape rather the log-normal as is the case with turbulence channel reported in [14].

Furthermore, Table III illustrates the visibility values corresponding to the measured values of T, the Q-factor corresponding to the BER and the eye height for P_{opt} of 0.56 dBm. As the amount of fog particles inside the chamber increases the corresponding visibility decreases, thus resulting in increased scattering of the optical beam. This in turn causes the distribution of bits ‘1’ and ‘0’ to be more flat due to the loss in the height (opening) of the eye diagram. The magnitude of the eye height drops from 6.27 mV to 0.022 mV from moderate to thick fog conditions as the visibility also drops from 418 to 70 m.

Table II
EXPERIMENTAL MEASURED VALUES FOR 0.56 dBm TRANSMITTED SIGNAL

Visibility (m)	Q-Factor	Eye Height (mV)	BER
418	7.0	6.27	1.2×10^{-12}
300	6.2	5.15	2.0×10^{-10}
138	5.0	2.96	2.8×10^{-7}
103	3.9	1.51	9.3×10^{-5}
70	2.36	0.022	9.1×10^{-3}

V. CONCLUSION

In this paper, we have demonstrated the effect of fog on the FSO link BER performance by observing transmittance values for a range of received optical power. The FSO system is set to work at the link margin therefore we could investigate the effects of different fog levels. We also observed that the profile or the histogram of the bit distribution is Gaussian even in the dense fog condition. The effects of low to high visibility on the FSO link BER performance in the presence of fog is also measured and investigated. We also showed that increasing the transmit optical power (within the eye safety margin) is one approach to mitigate the effect of the thick and dense fog without the need for wavelength diversity. Work to investigate wavelength diversity in fog is going on and would be published in due course.

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